PCT/GB 9 9 / 0 1 5 5 6

The Patent Office

INVESTOR IN PEOPLE

GP

9B99/1556

The Patent Office
Concept House
Cardiff Road
Newport
South Wales
NP10 8QQ

REC'D 2 1 JUN 1999
WIPO PCT

I, the undersigned, being an officer duly authorised in accordance with Section 74(1) and (4) of the Deregulation & Contracting Out Act 1994, to sign and issue certificates on behalf of the Comptroller-General, hereby certify that annexed hereto is a true copy of the documents as originally filed in connection with the patent application identified therein.

In accordance with the Patents (Companies Re-registration) Rules 1982, if a company named in this certificate and any accompanying documents has re-registered under the Companies Act 1980 with the same name as that with which it was registered immediately before re-registration save for the substitution as, or inclusion as, the last part of the name of the words "public limited company" or their equivalents in Welsh, references to the name of the company in this certificate and any accompanying documents shall be treated as references to the name with which it is so re-registered.

In accordance with the rules, the words "public limited company" may be replaced by p.l.c., plc, P.L.C. or PLC.

Re-registration under the Companies Act does not constitute a new legal entity but merely subjects the company to certain additional company law rules.

PRIORITY DOCUMENT

SUBMITTED OR TRANSMITTED IN COMPLIANCE WITH RULE 17.1(a) OR (b)

Signed

Dated 16 JUN 1999

12MAY99 E446500-1 D10013
01/7700 0.00 - 9910960.5

THE PATENT OFFICE
A
12 MAY 1999
RECEIVED BY FAX

Patents Form 1/77

Patents Act 1977
(Rule 16)

The Patent Office

Request for grant of a patent

(See the notes on the back of this form. You can also get an explanatory leaflet from the Patent Office to help you fill in this form)

The Patent Office

Cardiff Road
Newport
Gwent NP9 1RH

1. Your reference SPEC CAL

2. Patent application number *(The Patent Office will fill in this part)* **9910960.5** 12 MAY 1999

3. Full name, address and postcode of the or each applicant *(Underline all surnames)*

Patents ADP number *(if you know it)*

If the applicant is a corporate body, give the country/state of its incorporation

Tricorder Technology plc
Unit 2, The Long Room
Royal Quay
Coppermill Lock
Summerhouse Lane
Harefield, Middx. UB9 6JA

United Kingdom

7437684001

4. Title of the invention Method and Apparatus for deriving 3D representation

5. Name of your agent *(if you have one)*

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

R. G. V. Doble
38 Spring St
London W2 1JA

Patents ADP number *(if you know it)* 7607971001

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or each of these earlier applications and *(if you know it)* the or each application number

Country	Priority application number *(if you know it)*	Date of filing *(day / month /year)*

7. If this application is divided or otherwise derived from an earlier UK application, give the number and filing date of the earlier application

Number of earlier application	Date of filing *(day / month /year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:*

a) any applicant named in part 3 is not an inventor, or

b) there is an inventor who is not named as an applicant, or

c) any named applicant is a corporate body.

See note (d0)

Yes

THE PATENT OFFICE
A
12 MAY ...
RECEIVED BY FAX

Patents Form 1/77

9. Enter the number of sheets for any of the following items you are filing with this form. Do not count copies of the same document

Continuation sheets of this form	-
Description	16
Claim(s)	6
Abstract	1
Drawing(s)	6

10. If you are also filing any of the following, state how many against each item

Priority documents	
Translation of priority documents	
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	
Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(Please specify)*	

11. I/We request the grant of a patent on the basis of this application

Signature R. Doble Date 12.5.99

12. Name and daytime telephone number of person to contact in the United Kingdom — Richard Doble Tel: 0171 262 2435

Warning

After an application for a patent has been filed, the Comptroller of the Patent Office will consider wherher publication or communication of the invention should be prohibited or restricted under Section 32 of the Patents Act 1977. You will be informed if it is necessary to prohibit or restrict your invention in this way. Furthermore, if you live in the United Kingdom, Section 23 of the Patents Act 1977 stops you from applying for a patent abroad without first getting written permission from the Patent Office unless an application has been filed at least 6 weeks beforehand in the United Kingdom for a patent for the same invention and either no direction prohibiting publication or communication has been given, or any such direction has been revoked.

Notes

a) If you need help to fill in this form or you have any questions, please contact the Patent Office on 00645 500 505.
b)Write your answers in capital letters using black ink or you may type them.
c) If there is not enough space for all the relevant details on any part of this form, please continue on a separate sheet of paper and write "see coninuation sheet" in the relevant part(s). Any continuation sheet sould be attached to this form.
d) If you have answered 'Yes' Patents Form 7/77 will need to be filed.
e) Once you have filled in the form you must remember to sign and date it.
f) For details of the fee and ways to pay please contact the Patent Office.

Method and Apparatus for deriving 3D Representation

The present invention relates to a method and apparatus for deriving a representation of the three-dimensional (3D) shape of an object from an image (referred to herein as an object image) of the projection of structured optical radiation onto the object surface. The term "structured optical radiation" is a generalisation of the term "structured light" and is intended to cover not only structured light but also structured electromagnetic radiation of other wavelengths which obeys the laws of optics.

In principle the 3D shape of part of an object surface can be obtained by projecting structured light, eg a grid pattern onto a surface of the object, acquiring an image of the illuminated region of the object surface and identifying the elements of the structured light (eg the crossed lines of the grid pattern) which correspond to the respective features (eg crossed lines) of the image, assuming that the spatial distribution of the structured light is known.

One such arrangement is shown by Hu & Stockman in "3-D Surface Solution Using Structured Light and Constraint Propagation" in *IEEE Trans PAMI* Vol 2 No 4 pp 390 - 402, 1989, who discuss the advantages of the technique over stereoscopic imaging techniques in which two cameras acquire overlapping images of a common surface region of an object and the 3D shape is reconstructed from a correlation of pairs of features of the two images which correspond to the same physical surface feature. In particular the "correspondence problem" of correlating features in the two images obtained in stereoscopic imaging reduces to a much simpler "line labelling problem" when stripes are projected onto the object surface. Various geometric constraints are disclosed which simplify this problem further. The projection of both grids and grey scale patterns is disclosed.

In the arrangement shown in WO 93/03579 two projectors each project a set of light planes diverging from a line origin, the sets of light planes being mutually orthogonal and being directed onto a common region of the object surface to form a grid pattern. The line origins intersect at a point between the projectors above the object; this point is effectively the origin (optical centre) of a virtual projector.

A camera is arranged to acquire an image of the grid pattern as distorted by the

object surface and is so oriented with respect to the projector arrangement that the plane defined by a) the baseline joining the optical centres of the virtual projector and b) the optical axis of the camera is nearly parallel to one set of light planes. This ensures that the stripes in the image corresponding to this set of light planes cross only a small number of stripes derived from the other set of light planes and that the number of possible pairs of light planes corresponding to a given intersection of stripes in the acquired image is reduced to a minimum. Since each intersection can be associated with only one pair of light planes the potential ambiguity in the image reconstruction is reduced.

The above problem of ambiguity is addressed in the context of stereoscopic imaging by WO91/15732 (Gordon) which discloses an arrangement in which a laser scanner projects a series of stripes onto the scanned object and left and right cameras detect the distorted stripes from the object.

It is recognised that a given bright point in the image plane of one camera cannot be simply correlated with an illuminated point on the surface of the object because it is not known which stripe illuminates that point. Accordingly, an arbitrary pixel in the stripe in one camera's image plane is selected and a line drawn through the centre of the camera lens projecting this line out into space. This line is then projected onto the image plane of the other camera and the resulting epipolar line in the other camera's image plane cuts a number of stripes also imaged on its image plane. Any one of these points of intersection could in principle correspond to the arbitrary pixel mentioned above. The particular point which corresponds is found by projecting all the points of intersection back into space and determining which of the resulting lines intersects a laser stripe from the laser projector.

US 5,838,428 discloses an arrangement employing successively projected patterns of stripes, coded in accordance with a DeBruijn sequence and blurred to enable the resolution of the arrangement to be increased by interpolation. The projector comprises a mask and a xenon flash tube. The code is such that each element in the CCD photodetector used to image the projection of the pattern on the object surface detects a unique sequence of grey levels which is determined by the 3D position of the corresponding surface portion of the object and the structure of the projected light. The latter is found by a calibration procedure involving imaging the same sequence of projections on a reference plane.

It should be noted that there is no correlation of images in the calibration or measurement procedure.

Although the above arrangement avoids the correspondence or line labelling problem it has the disadvantage of requiring multiple projections of structured light and acquisition of images, increasing the complexity and reducing the speed of the arrangement. In particular the shape of a moving or shape-changing object cannot be determined. Furthermore the calibration procedure is complex.

An object of the present invention is to alleviate or overcome at least some disadvantages of the prior art.

In one aspect the invention provides apparatus for generating a 3D representation of at least part of an object from an object image of the projection of structured optical radiation onto the object surface and from at least one calibration image of the projection of the structured optical radiation onto a surface displaced from the object surface, the apparatus comprising image processing means arranged to generate correspondences between at least one calibration image and the object image and optionally a further calibration image, and reconstruction processing means arranged to simulate a first projection of the object image and a second projection linking respective correspondences of at least two of the correlated images and to derive said 3D representation from the mutual intersections of the first and second projections.

The calibration image can for example be of the projection of the structured optical radiation onto a calibration surface or can for example be a further object image obtained after moving the object relative to the camera used to acquire the initial object image and the projector means used to project the structured optical radiation.

Preferably the first and second projections are from a baseline linking an origin of the structured optical radiation and a perspective centre associated with the image (eg the optical centre of the camera lens used to acquire the image), the reconstruction processing means being arranged to derive said baseline from two or more pairs of correlated features. This feature is illustrated in Figures 2 and 11 discussed in detail below.

In one embodiment the image processing means is arranged to generate correspondences between two or more calibration images and to determine the spacing between origins of the first and second projections in dependence upon both the correspondences of the two or more calibration images and input or stored metric information associated with the calibration images. This feature is illustrated in

Figure 11, discussed in detail below.

In another embodiment the reconstruction processing means is arranged to vary the spacing between the origins of the first and second projections in dependence upon a scaling variable enterable by a user. In this embodiment a further calibration image is not required. Preferably the apparatus includes means for displaying the 3D representation with a relative scaling dependent upon the value of the scaling variable.

Preferably the apparatus includes means for combining two or more 3D representations and means for adjusting the relative scaling of the representations to enable them to fit each other.

Preferably the image processing means is arranged to generate said correspondences of said images by comparing local radiometric distributions of said images.

Suitable algorithms for correlating (generating correspondences between) overlapping images are already known - eg Gruen's algorithm (see Gruen, A W "Adaptive least squares correlation: a powerful image matching technique"*S Afr J of Photogrammetry, remote sensing and Cartography* Vol 14 No 3 (1985) and Gruen, A W and Baltsavias, E P "High precision image matching for digital terrain model generation" *Int Arch photogrammetry* Vol 25 No 3 (1986) p254) and particularly the "region-growing" modification thereto which is described in Otto and Chau "Region-growing algorithm for matching terrain images" *Image and Vision Computing Vol* 7 No 2 May 1989 p83, all of which are incorporated herein by reference.

Essentially, Gruen's algorithm is an adaptive least squares correlation algorithm in which two image patches of typically 15 x 15 to 30 x 30 pixels are correlated (ie selected from larger left and right images in such a manner as to give the most consistent match between patches) by allowing an affine geometric distortion between coordinates in the images (ie stretching or compression in which originally parallel lines remain parallel in the transformation) and allowing an additive radiometric distortion between the grey levels of the pixels in the image patches, generating an over-constrained set of linear equations representing the discrepancies between the correlated pixels and finding a least squares solution which minimises

the discrepancies.

The Gruen algorithm is essentially an iterative algorithm and requires a reasonable approximation for the correlation to be fed in before it will converge to the correct solution. The Otto and Chau region-growing algorithm begins with an approximate match between a point in one image and a point in the other, utilises Gruen's algorithm to produce a more accurate match and to generate the geometric and radiometric distortion parameters, and uses the distortion parameters to predict approximate matches for points in the region of the neighbourhood of the initial matching point. The neighbouring points are selected by choosing the adjacent points on a grid having a grid spacing of eg 5 or 10 pixels in order to avoid running Gruen's algorithm for every pixel.

Hu *et al* "Matching Point Features with ordered Geometric, Rigidity and Disparity Constraints" IEEE Transactions on Pattern Analysis and Machine Intelligence Vol 16 No 10, 1994 pp1041-1049 (and references cited therein) discloses further methods for correlating features of overlapping images.

Since the above algorithms were developed for generating correspondences between images having poorly defined features (eg aerial photographs) whereas the projection of structured light onto an object surface will generate distinct local radiometric distributions, the problem of correlation is less critical in the context of the present invention. Accordingly the precise correlation algorithm is not critical. However we have found a number of improvements to the Gruen algorithm, as follows:

i) the additive radiometric shift employed in the algorithm can be dispensed with;

ii) if during successive iterations, a candidate matched point moves by more than a certain amount (eg 3 pixels) per iteration then it is not a valid matched point and should be rejected;

iii) during the growing of a matched region it is useful to check for sufficient contrast at at least three of the four sides of the region in order to ensure that there is sufficient data for a stable convergence - in order to facilitate this it is desirable to make the algorithm configurable to enable the parameters (eg required contrast) to

be optimised for different environments, and

iv) in order to quantify the validity of the correspondences between images it has been found useful to re-derive the original grid point in the starting image by applying the algorithm to the matched point in the other image (ie reversing the stereo matching process) and measuring the distance between the original grid point and the new grid point found in the starting image from the reverse stereo matching. The smaller the distance the better the correspondence.

In another aspect the invention provides apparatus for deriving a 3D representation of at least part of an object, comprising means for projecting structured optical radiation onto the surface of the object, means for acquiring a 2D image of the projection of the structured optical radiation, and image processing means arranged to derive the 3D representation from the distortion of the structure of the projected optical radiation by the object surface, the projected structured optical radiation having an irregular radiometric and/or colorimetric distribution.

In a related aspect the invention provides a method of generating a 3D representation of at least part of an object, wherein structured optical radiation is projected onto the surface of the object, a 2D image of the projection of the structured optical radiation on the surface is acquired, and the 3D representation is derived from the distortion of the structure of the projected optical radiation by the object surface, the projected structured optical radiation having an irregular radiometric and/or colorimetric distribution.

In a further aspect the invention provides a method of generating a 3D representation of at least part of an object from an object image of the projection of structured optical radiation onto the object surface and from at least one calibration image of the projection of the structured optical radiation onto a surface displaced from the object surface, the method comprising the steps of:

i) correlating at least one calibration image with the object image and optionally with a further calibration image;

ii) simulating a first projection of the object image and a second projection of the structured optical radiation, and

iii) deriving said 3D representation from the mutual intersections of the first and second projections.

In a related aspect the invention provides image processing apparatus for deriving a 3D representation of at least part of an object from a 2D image of the illuminated object, the object being illuminated with structured optical radiation projected from a location spaced apart from the viewpoint at which the 2D image is acquired, the 2D image being correlated with the structured radiation, the apparatus comprising digital processing means arranged to form a 3D reconstruction in which an illuminated region of the object in the image extends in a simulated 3D space in dependence upon both the correlation and a scaling variable, the scaling variable being representative of the separation between the location from which the structured optical radiation is projected and the viewpoint at which the 2D image is acquired.

Preferred features of the invention are defined in the dependent claims.

In another aspect the invention provides image processing apparatus for deriving a 3D representation of at least part of an object from a 2D image thereof, the object being illuminated with structured optical radiation projected from a location spaced apart from the viewpoint at which the 2D image is acquired, the 2D image being correlated with rays of the structured radiation, the apparatus comprising digital processing means arranged to form a 3D reconstruction which extends in a simulated 3D space in dependence upon both the correlation and a scaling variable, the scaling variable being representative of the separation between the location from which the structured optical radiation is projected and the viewpoint at which the 2D image is acquired.

This aspect of the invention is illustrated in Figure 6. Following a simple calibration procedure requiring no knowledge of the position of the camera or the projector relative to the object it enables a 3D representation to be generated. This can optionally be displayed and scaled or it can be distorted eg for special effects in graphics and animation.

Preferably the apparatus is arranged to derive a further 3D reconstruction from a

further 2D image acquired from a different viewpoint relative to the object, the combining means being arranged to combine the first-mentioned 3D reconstruction and the further 3D reconstruction by manipulations in a simulated 3D space involving one or more of rotation and translation, the apparatus further comprising scaling means arranged to reduce or eliminate any remaining discrepancies between the 3D reconstructions by scaling one 3D reconstruction relative to the other along at least one axis.

Preferably the apparatus is arranged to display both 3D reconstructions simultaneously and to manipulate them in simulated 3D space in response to commands entered by a user.

In one embodiment the apparatus is arranged to perform the manipulations of the 3D reconstructions under the control of a computer pointing device.

In a related aspect the invention provides a method of deriving a 3D representation of at least part of an object from a 2D image thereof, comprising the steps of illuminating the object with structured projected optical radiation, acquiring a 2D image of the illuminated object, correlating the 2D image with rays of the structured optical radiation, and digitally processing the 2D image to form a 3D reconstruction which extends in a simulated 3D space in dependence upon both the correlation and a scaling variable, the scaling variable being representative of the separation between a location from which the structured optical radiation is projected and the viewpoint at which the 2D image is acquired.

Preferred embodiments of the invention are described below by way of example only with reference to Figures 1 to 11 of the accompanying drawings, wherein:

Figure 1 is a schematic representation of apparatus in accordance with all aspects of the invention;

Figure 2 is a sketch perspective ray diagram showing the optical arrangement of the apparatus of Figure 1;

Figure 3 shows an object image and a calibration image acquired by the apparatus of Figures 1 and 2 and the correlation of their features;

Figure 4 is a sketch perspective ray diagram showing the use of two reference surfaces to locate the camera and projector of the apparatus of Figures 1 and 2 on the baseline connecting their respective perspective centres;

Figure 5 is a flow diagram illustrating the mode of operation of the apparatus of Figures 1 and 2 in accordance with the first method aspect of the invention;

Figure 6 is a ray diagram illustrating both the acquisition of the images utilised by the apparatus of Figures 1 and 2 and the regeneration of the object shape by virtual projectors of the acquired object image and structured optical radiation;

Figure 7 is a screenshot illustrating the fitting together of two 3D surface portions of the object using the apparatus of Figures 1 and 2;

Figure 8 is further screenshot showing the scaling of the resulting composite 3D surface portion along vertical and horizontal axes;

Figure 9 is a further screenshot showing the scaling of intersecting 3D surface portions to fit each other;

Figure 10 is a screenshot showing a user interface provided by the apparatus of Figures 1 and 2 for manipulating the images and 3D surface portions, and

Figure 11 is a 3D ray diagram showing the derivation of the projector-camera separation from the position of two reference or target surfaces.

Referring to Figure 1, the apparatus comprises a personal computer 4 (eg a Pentium® PC) having conventional CPU, ROM, RAM and a hard drive and a frame grabber connection at an input port to a digital camera 1 as well as a video output port connected to a screen 5 and conventional input ports connected to a keyboard and a mouse 6 or other pointing device. The hard drive is loaded with conventional operating system such as Windows®95 and software:

a) to display images acquired by the camera 1;

b) to generate correspondences between overlapping regions of images input from the camera 1;

c) to derive from the acquired images the baseline joining the perspective centres of the camera and projector;

d) to project images acquired by the camera into a simulated 3D space from virtual projectors located on the baseline at a separation selected (with the keyboard or pointing device) by the user or determined (thereby creating a partial 3D reconstruction);

e) to scale the partial 3D reconstruction along one or more axes and combine such partial 3D reconstructions as illustrated in Figures 7, 8 and 9, and

f) to determine the separation of the perspective centres of the camera and projector along the baseline from further correlations of object images and calibration images, and thence derive an accurate partial 3D reconstruction of the object surface.

Additionally the software is preferably arranged to correct the images for distortion due eg to curvature of field of the camera and projector optics before they are processed as described above, either during an initial calibration procedure or as part of a ray bundle adjustment process during the processing of the object and calibration image(s). Suitable correction and calibration procedures are described by Tsai in "An Efficient and Accurate Camera Calibration Technique for 3D Machine Vision" *Proc IEEE CVPR* (1986) pp 364-374 and will not be described further.

The camera, a Pulnix M-9701 progressive scan digital camera, is shown mounted at one end of a support frame F on eg a ball and socket mounting and a slide projector PR is shown securely mounted on the other end of the frame. Slide projector PR is provided with a speckle pattern slide S and is arranged to project the resulting speckle pattern onto the surface of region R of an object 3 which is in the field of view of camera CM.

The intrinsic camera parameters are initially determined by acquiring images of a reference plate (not shown) in known positions. The reference plate is planar and has an array of printed blobs of uniform and known spacing. The following parameters

are determined and are therefore assumed to be known in the subsequent description:

i) focal length of the camera
ii) distortion parameters of the lenses of the camera and projector
iii) scale factor
iv) image coordinates of principal point.

Additionally the pixel size (determined by the camera manucturer) is assumed to be known.

Optionally, the following extrinsic camera parameters are determined:

a) camera location
b) camera orientation.

Alternatively the camera location and orientation can be taken to define the coordinate system relative to which the object surface coordinates are determined.

Referring now to Figure 2, the camera CM is shown with its perspective centre O_C located on a baseline vector V and viewing (initially) a target surface T and (subsequently) object 3. The (virtual) origin or perspective centre Op of projector PR also lies on baseline vector V and is defined by the optical system of the projector comprising field lenses OL and condenser lenses CL. A point light source LS such as a filament bulb illuminates slide S and directs a speckle pattern onto (initially) target surface T and (subsequently) the surface of object 3.

The baseline vector V is found by the following procedure:

Firstly an image I1 (Figure 3) of the region of the surface of object 3 illuminated by the projected speckle pattern is acquired and stored in the memory of computer 4 and an arbitrary group of at least two spaced apart points Q1 and Q2 of this region are selected as points q1 and q2 in the image formed on the photodetector plane PD of the camera. The group of points q1 and q2 is stored.

Secondly the object 3 is substituted by target surface T and an image I2 (Figure 3) of

the illuminated region of the target surface is acquired by camera CM. The position and orientation of the target T relative to the camera are found by acquiring an image of the target in the absence of any illumination from the projector, utilising a known pattern of blobs BL formed on the periphery of the target. The image I2 is stored and and a patch defined by its central point (eg Q_n, Figure 3) of the first image I1 is correlated with the corresponding point P_n of the second image I2 by selecting a surrounding region R of initially 3 x 3 pixels and, by comparing local radiometric intensity distributions by means of the above-described modified Gruens algorithm, searching for the corresponding region R' in image I2 which is allowed to be distorted with an affine geometric distortion (eg in the simple case illustrated in Figure 3, horizontally elongated). The correlated patch is expanded (up to a maximum of 19 x 19 pixels) and the process is repeated. In this manner the corresponding point P_n is found.

This process is repeated to find a large number of pairs of correspondences PQ (Figure 3) and in particular to correlate the patches centered on P1, P2 (Figure 2) with the points in the group Q1, Q2 (Figure 2). Since the algorithm has a sub-pixel resolution, the latter are not necessarily centred on particular pixels.

In the following geometric discussion the correspondences are treated for the sake of simplicity as correlated pairs of points but it should be noted that this does not imply anything about their topography - in particular it does not imply that they lie at corners or edges of the object, for example.

Referring to Figure 2, the origin (perspective centre) of the projector PR will lie at the intersection of P1Q1 and P2Q2. However the 3D locations of these four points are not known, only the ray lines from the camera on which they lie, namely p1P1, q1Q1, p2P2 and q2Q2. But the line P1Q1 will lie in the plane O_CP1Q1 ie plane O_Cp1q1 which is available form the calibration process and the two images I1 and I2 and the line P2Q2 will lie in the plane O_CP2Q2 ie plane O_Cp2q2 which is similarly available from the calibration process and the two images I1 and I2. These planes define a baseline vector V by their intersection, which passes through OC and the perspective centre Op of the projector.

A particularly simple way of finding the baseline vector V is to project p1q1 and p2q2 which will meet at a point X in the plane of photodetector PD. The projection

from point X through the perspective centre O_C is the baseline vector V as shown.

In this manner the baseline vector V can be determined, though not the position of the projector origin Op along this baseline. In practice the groups of points P and Q will each comprise more than two pairs and hence overdetermine the baseline vector V. Accordingly the computer 4 is preferably arranged to derive a bundle of such vectors as determined by the sets of points PQ, to eliminate "outliers" ie those vectors which deviate by more than a given threshold from the mean and to perform a least squares estimate of vector V on the remainder of the vectors, in accordance with known statistical methods.

The derivation of a three-dimensional representation of the object 3 is shown in the ray diagram of Figure 6.

The camera CM and projector PR are shown located on baseline vector V. A first virtual projector pr1 is implemented by the image processing software in computer 4 and has the same optical characteristics as the camera (as determined in the initial calibration procedure). Image I1 (Figure 3) is projected from this virtual projector in a 3D space simulated by the image processing software.

A second virtual projector pr2 is similarly implemented by the image processing software and preferably has the same optical characteristics as the projector PR (which is also represented in Figure 6). This virtual projector projects a set of ray lines in the simulated 3D space corresponding to the respective physical projector rays PQ and the ray lines are each labelled with the respective correlated pixels of the image I1 as found in the image correlation process described with reference to Figure 3. It will be appreciated that the image I2 and target T define, and can be equated with, a set of rays originating from the perspective centre OP of the projector. Since it is known which ray line from the projector PR/pr1 intersects each ray line from its corresponding pixel in image I1, the point in 3D space corresponding to each intersection can be found, and hence the set of points Qa, Qb, Qc... defining the surface.

In practice many ray lines will not intersect and the best estimate of the corresponding 3D surface point will be the mid-point of the perpendicular line joining them at their closest approach. Algorithms for this purpose are known *per se*.

In the above discussion of Figure 6 it has been assumed that the relative positions of the camera CM and and projector PR on baseline vector V (and hence the positions of the virtual projectors pr1 and pr2) are known. In fact these are assumed or entered as a scaling variable by the user of the computer 4.

That the ray lines from the respective virtual projectors will intersect irrespective of the spacing between the virtual projectors, assuming that their orientations are unchanged, is illustrated in Figure 6 by the alternative virtual projector position pr2' corresponding to an assumed real projector position PR'. The resulting 3D reconstruction of the object 3' will be different in size but of the same shape: a single scaling factor will be required to interconvert objects 3 and 3'. However it may be convenient in practice to provide for different horizontal and vertical scaling factors (eg because of different horizontal and vertical magnifications of the camera) and in general only one set of scaling factors will be consistent with fitting together a set of partial 3D surfaces of the same object acquired from different directions.

Accordingly the software in computer 4 is arranged to scale such acquired 3D representations to enable them to be fitted together to form a self-consistent overall 3D representation of the object. This aspect is described below with reference to Figures 7 to 10.

Before doing so however, an alternative calibration procedure will be described with reference to Figure 4, which shows two planar calibration targets T1 and T2 (having peripheral blobs or discs BL similar to target T of Figure 2) whose orientations and positions relative to the camera axis system are known, eg as a result of a photogrammetric determination involving separately acquiring images of them in the absence of any illumination from the projector, and processing the images in a procedure similar to that described above in connection with Figure 2. The perspective centres O_C and O_P of the camera and projector are also shown.

In a first stage of the calibration procedure, target T1 is illuminated by the structured light from the projector and an image is acquired by the camera CM. Figure 4 illustrates three points p1, p2 and p3 at which the structured light impinges on target T1. These (and many other points, not shown) will be imaged by the camera CM.

In a second stage of the calibration procedure, target T1 is removed and target T2 is illuminated by the structured light from the projector. An image is acquired by the camera CM. The three points P1, P2 and P3 corresponding to points p1, p2 and p3 are found by correlating the newly acquired image of the projection of the structured radiation on target T2 with the previously acquired image of the corresponding projection on T1 by the procedure described above with reference to Figure 3.

Figure 11 illustrates further the relationship between the positions of two calibration targets T1 and T2 and the perspective centre Op of the projector PR (the camera CM being assumed fixed on the baseline vector V). A pair of points P1 and P2 on target T1 form image points p1 and p2 respectively on the photodetector array PD of camera CM and (in a subsequent step following the removal of target T1) a pair of points P3 and P4 on target T2 which are correlated with P1 and P2 respectively form image points p3 and p4 respectively on photo detector array PD.

Accordingly in a third stage the pencil of rays formed by corresponding points on targets T1 and T2 (eg P1 and P3; P2 and P4) is constructed to find the position of the perspective centre Op of the projector. In practice the rays will not intersect at a point but a best estimate can be found from a least squares algorithm.

It will be appreciated that other calibration procedures are possible. For example the camera could be calibrated by the Tsai method (Roger Y Tsai, *IEEE Journal of Robotics and Automation* RA-3, No 4, August 1987 p 323 - see also references cited therein).

Figures 7 to 10 illustrate the fitting together and manipulation of the partial 3D reconstructions on screen.

In Figure 7 a partial 3D reconstruction R1 and a partial 3D reconstruction R2 are fitted together at their corresponding points F and F', A and A' and result in a composite (but still incomplete) 3D reconstruction R3 as shown in Figure 13 having an array comprising points E, B and D from R1 and points C' and G' in defined positions which can be fitted to a further partial 3D reconstruction R4 as shown in Figure 8.

Referring to Figure 8, it is assumed that faces ABC, DGCB, DGEF and ABDEF of

R4 are formed but that the region bounded by points A, C , G and F is not. The user rotates R3 on screen using eg mouse 6 (Figure 1) to give a rotated partial 3D representation R3' which is aligned with R4 and which he/she then sees is horizontally compressed relative to R4. Accordingly R3 can be expanded horizontally or R4 can be compressed horizontally to enable them to be fitted together to form a self consistent, complete 3D representation of the object R5.

As shown in Figure 9, this can be compressed or expanded along any desired axis or otherwise distorted under the control of the user to produce a final representation R6 or R6' having any desired relationship with the actual object 3.

Figure 10 shows a screen shot of the user interface generated by a program for manipulating the 3D reconstructions 30. Buttons BN are provided which can be clicked on by the mouse under the control of the user and,when thus selected, enable the user to drag portions of the displayed representation so as to zoom, rotate and pan the view of the object, as well as to come closer to and move away from the object ("nearer" and "further" buttons respectively). As described this far, the interface is similar to the publicly available interface of the COSMO PLAYER web browser plug-in produced by Cosmo Software Inc, of California USA. However, in accordance with a feature of the present invention, "wheels" W1 and W2 are provided which are rotatable by the mouse and enable the user to adjust the separation between the virtual projectors and to vary the distance to the object respectively. The latter control is effectively a perspective control. Optionally, further buttons or other means (not shown) may be provided to enable distortions (such as those described above) to be applied in a graphical fashion, or to enable other distortions such as shear distortion to be applied.

Preferred features of any aspect of the invention can be combined with any other aspect of the invention.

Claims

1. Apparatus for generating a 3D representation of at least part of an object from an object image of the projection of structured optical radiation onto the object surface and from at least one calibration image of the projection of the structured optical radiation onto a surface displaced from the object surface, the apparatus comprising image processing means arranged to generate correspondences between at least one calibration image and the object image and optionally a further calibration image, and reconstruction processing means arranged to simulate a first projection of the object image and a second projection linking respective correspondences of at least two of the correlated images and to derive said 3D representation from the mutual intersections of the first and second projections.

2. Apparatus as claimed in claim 1 wherein the first and second projections are from a baseline linking an origin of the structured optical radiation and a perspective centre associated with the images, the reconstruction processing means being arranged to derive said baseline from the correlation.

3. Apparatus as claimed in claim 1 or claim 2 wherein the image processing means is arranged to correlate two or more calibration images and to determine the spacing between origins of the first and second projections in dependence upon both the correlation of the two or more calibration images and input or stored metric information associated with the calibration .

4. Apparatus as claimed in any preceding claim wherein the reconstruction processing means is arranged to vary the spacing between the origins of the first and second projections in dependence upon a scaling variable enterable by a user.

5. Apparatus as claimed in claim 4 including means for displaying the 3D representation with a relative scaling dependent upon the value of the scaling variable.

6. Apparatus as claimed in any preceding claim including means for combining two or more 3D representations and means for adjusting the relative scaling of the representations to enable them to fit each other.

7. Apparatus as claimed in any preceding claim wherein the image processing means is arranged to correlate pixels in one of said images with corresponding locations in the other of said images by comparing the local radiometric distributions associated with said pixels and locations respectively.

8. Apparatus as claimed in claim 7 wherein the image processing means is arranged to allow a radiometric and/or geometric distortion during the correlation process.

9. Apparatus as claimed in any preceding claim further comprising projector means arranged to project the structured optical radiation onto the object surface and at least one calibration surface.

10. Apparatus for deriving a 3D representation of at least part of an object, comprising means for projecting structured optical radiation onto the surface of the object, means for acquiring a 2D image of the projection of the structured optical radiation, and image processing means arranged to derive the 3D representation from the distortion of the structure of the projected optical radiation by the object surface, the projected structured optical radiation having an irregular radiometric and/or colorimetric distribution.

11. Apparatus as claimed in claim 10 wherein the structured optical radiation comprises a distribution of three or more radiometric and/or colorimetric intensity values.

12. Apparatus as claimed in claim 10 or claim 11 wherein the structured optical radiation comprises a speckle pattern.

13. Apparatus as claimed in any of claims 10 to 12 wherein the structured optical radiation comprises a fractal pattern whose structure is invariant at different scales.

14. Apparatus as claimed in any of claims 10 to 13 wherein the projector means is arranged to project the structured radiation from a focal point or focal line defined by its optics.

15. Apparatus as claimed in any preceding claim further comprising a camera

arranged to acquire the object image and at least one calibration image.

16. Apparatus as claimed in any preceding claim further comprising at least one calibration target which in use is illuminated by the structured radiation.

17. A method of generating a 3D representation of at least part of an object, wherein structured optical radiation is projected onto the surface of the object, a 2D image of the projection of the structured optical radiation on the surface is acquired, and the 3D representation is derived from the distortion of the structure of the projected optical radiation by the object surface, the projected structured optical radiation having an irregular radiometric and/or colorimetric distribution.

18. A method of generating a 3D representation of an object from an object image of the projection of structured optical radiation onto the object surface and from at least one calibration image of the projection of the structured optical radiation onto a surface displaced from the object surface, the method comprising the steps of:

i) correlating at least one calibration image with the object image and optionally with a further calibration image;

ii) simulating a first projection of the object image and a second projection of the structured optical radiation, and

iii) deriving said 3D representation from the mutual intersections of the first and second projections.

19. A method as claimed in claim 18 wherein the first and second projections are from a baseline linking an origin of the structured optical radiation and a perspective centre associated with the image respectively, said baseline being derived from two or more pairs of correlated features.

20. A method as claimed in claim 23 or claim 24 wherein two or more calibration images are correlated and the spacing between origins of the first and second projections is determined in dependence upon both the correlation of the two or more calibration images and input or stored metric information associated with the calibration images.

21. A method as claimed in any of claims 18 to 20 wherein the spacing between the origins of the first and second projections is varied in dependence upon a scaling variable entered by a user.

22. A method as claimed in claim 21 wherein the 3D representation is displayed with a relative scaling dependent upon the value of the scaling variable.

23. A method as claimed in any of claims 18 to 22 wherein two or more 3D representations are combined and the relative scaling of the representations is adjusted along at least one axis to enable them to fit each other.

24. A method as claimed in any of claims18 to 23 wherein regions of said images are correlated by comparing the local radiometric and/or colorimetric distributions associated with said regions.

25. A method of generating a 3D representation of at least part of an object, wherein structured optical radiation is projected onto the surface of the object, a 2D image of the projection of the structured optical radiation on the surface is acquired, and the 3D representation is derived from the distortion of the structure of the projected optical radiation by the object surface, the projected structured optical radiation having an irregular radiometric and/or colorimetric distribution.

26. A method as claimed in claim 24 or claim 25 wherein a radiometric and/or geometric distortion is allowed between potentially corresponding regions.

27. Image processing apparatus for deriving a 3D representation of at least part of an object from a 2D image of the illuminated object, the object being illuminated with structured optical radiation projected from a location spaced apart from the viewpoint at which the 2D image is acquired, the 2D image being correlated with the structured radiation, the apparatus comprising digital processing means arranged to form a 3D reconstruction which extends in a simulated 3D space in dependence upon both the correlation and a scaling variable, the scaling variable being representative of the separation between the location from which the structured optical radiation is projected and the viewpoint at which the 2D image is acquired.

28. Apparatus as claimed in claim 27 which is arranged to derive a further 3D reconstruction from a further 2D image acquired from a different viewpoint relative to the object, the combining means being arranged to combine the first-mentioned 3D reconstruction and the further 3D reconstruction by manipulations in a simulated 3D space involving one or more of rotation and translation, the apparatus further comprising scaling means arranged to reduce or eliminate any remaining discrepancies between the 3D reconstructions by scaling one 3D reconstruction relative to the other along at least one axis.

29. Apparatus as claimed in claim 28 which is arranged to display both 3D reconstructions simultaneously and to manipulate them in simulated 3D space in response to commands entered by a user.

30. Apparatus as claimed in claim 29 which is arranged to perform the manipulations of the 3D reconstructions under the control of a computer pointing device.

31. A method of deriving a 3D representation of at least part of an object from a 2D image thereof, comprising the steps of illuminating the object with structured projected optical radiation, acquiring a 2D image of the illuminated object, correlating the 2D image with rays of the structured optical radiation, and digitally processing the 2D image to form a 3D reconstruction which extends in a simulated 3D space in dependence upon both the correlation and a scaling variable, the scaling variable being representative of the separation between a location from which the structured optical radiation is projected and the viewpoint at which the 2D image is acquired.

32. A method as claimed in claim 31 wherein a view of the reconstruction in the simulated 3D space is displayed on a screen and the scaling variable is entered by a user.

33. Apparatus for generating a 3D representation of at least part of an object, substantially as described hereinabove with reference to Figures 1 to 4 and 11 optionally modified in accordance with Figures 5 to 10 of the accompanying drawings.

34. A method of deriving a 3D representation of at least part of an object, substantially as described hereinabove with reference to Figures 1 to 4 and 11 optionally modified in accordance with Figures 5 to 10 of the accompanying drawings.

Abstract

Projective Image Processing Apparatus

An apparatus for deriving a 3D representation of at least part of an object (3) comprises a projector (PR) arranged to project a speckle pattern or other structured light from a slide (S) onto the object and a single digital camera (CM) arranged to acquire an image of the object and an image of a calibration target (T) which is similarly illuminated by the speckle pattern in a preliminary calibration step. Pairs of points (P1, Q1; P2, Q2) of the respective images are correlated eg by Gruen's algorithm to enable the baseline vector (V) joining the perspective centres (O_C, O_P) of the camera and projector to be found from the intersection of planes O_CP1Q1 and O_CP2Q2. The 3D representation is then generated in simulated 3D space by projection and intersection of ray bundles from virtual projectors (implemented in software) located on the baseline vector (V).

Figure 2

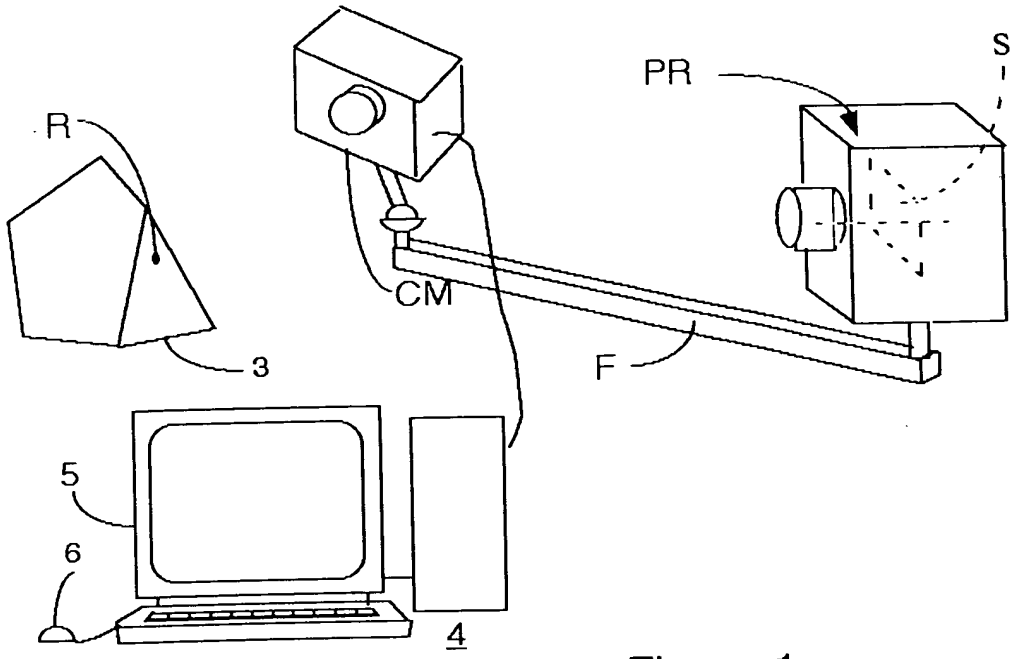

Figure 1

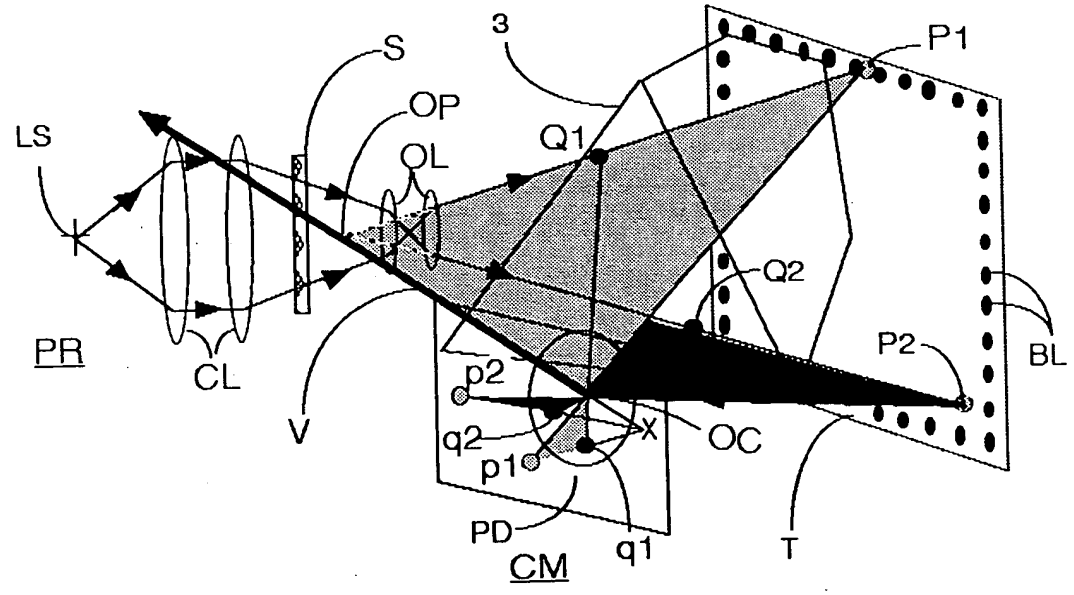

Figure 2

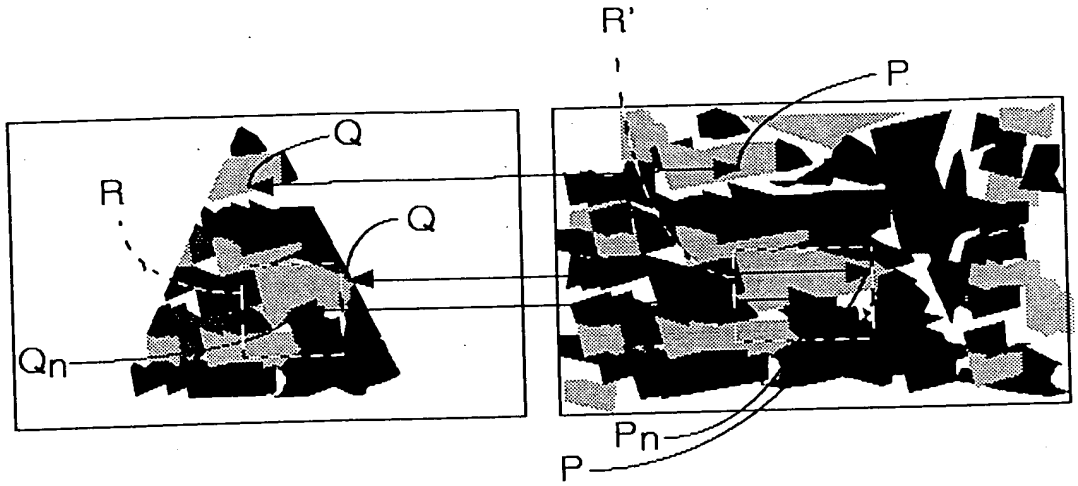

Figure 3

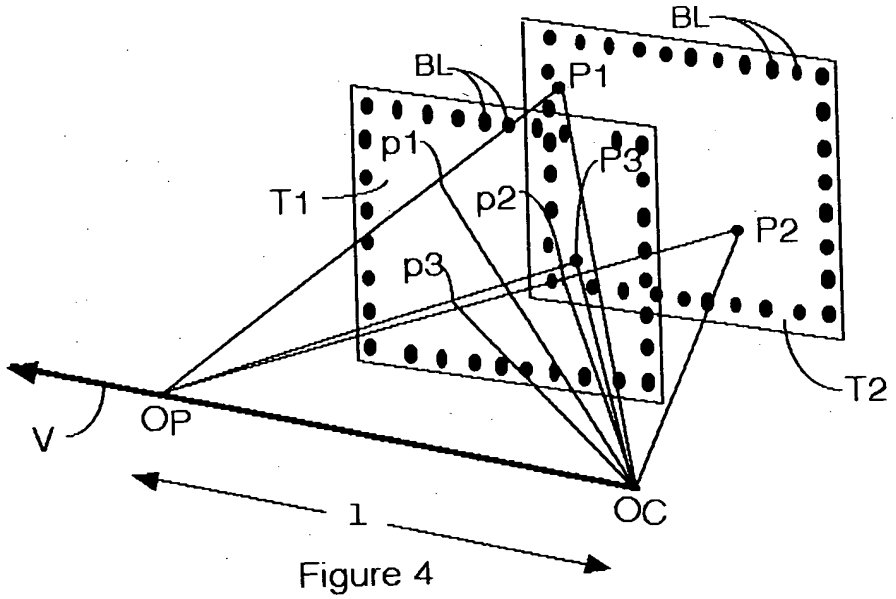

Figure 4

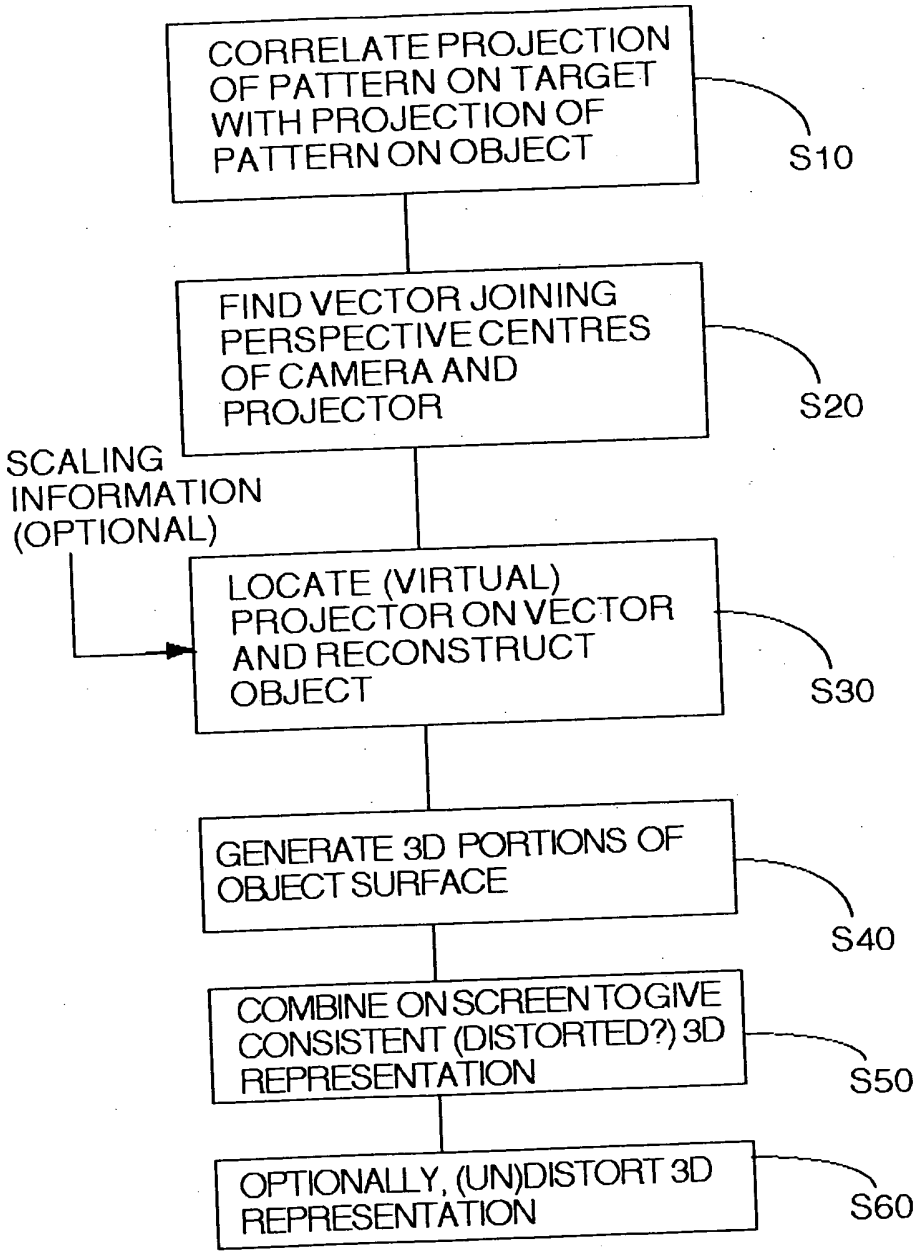
CORRELATE PROJECTION OF PATTERN ON TARGET WITH PROJECTION OF PATTERN ON OBJECT
S10
FIND VECTOR JOINING PERSPECTIVE CENTRES OF CAMERA AND PROJECTOR
S20
SCALING INFORMATION (OPTIONAL)
LOCATE (VIRTUAL) PROJECTOR ON VECTOR AND RECONSTRUCT OBJECT
S30
GENERATE 3D PORTIONS OF OBJECT SURFACE
S40
COMBINE ON SCREEN TO GIVE CONSISTENT (DISTORTED?) 3D REPRESENTATION
S50
OPTIONALLY, (UN)DISTORT 3D REPRESENTATION
S60

Figure 5

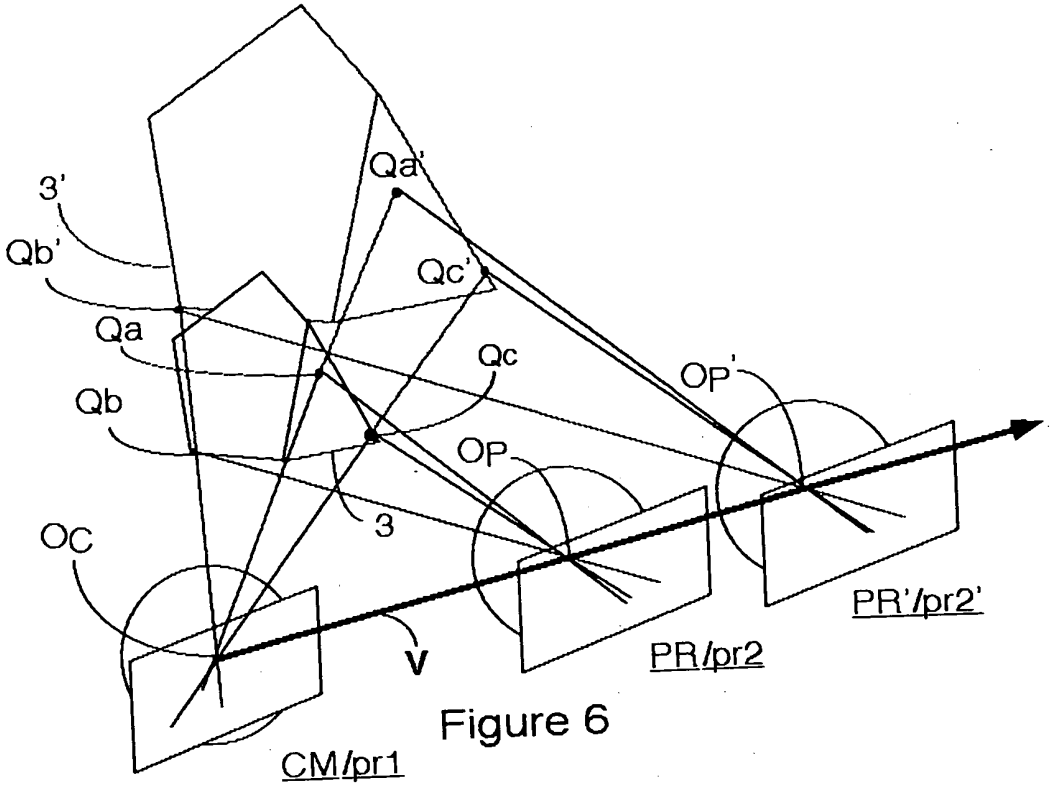

Figure 6

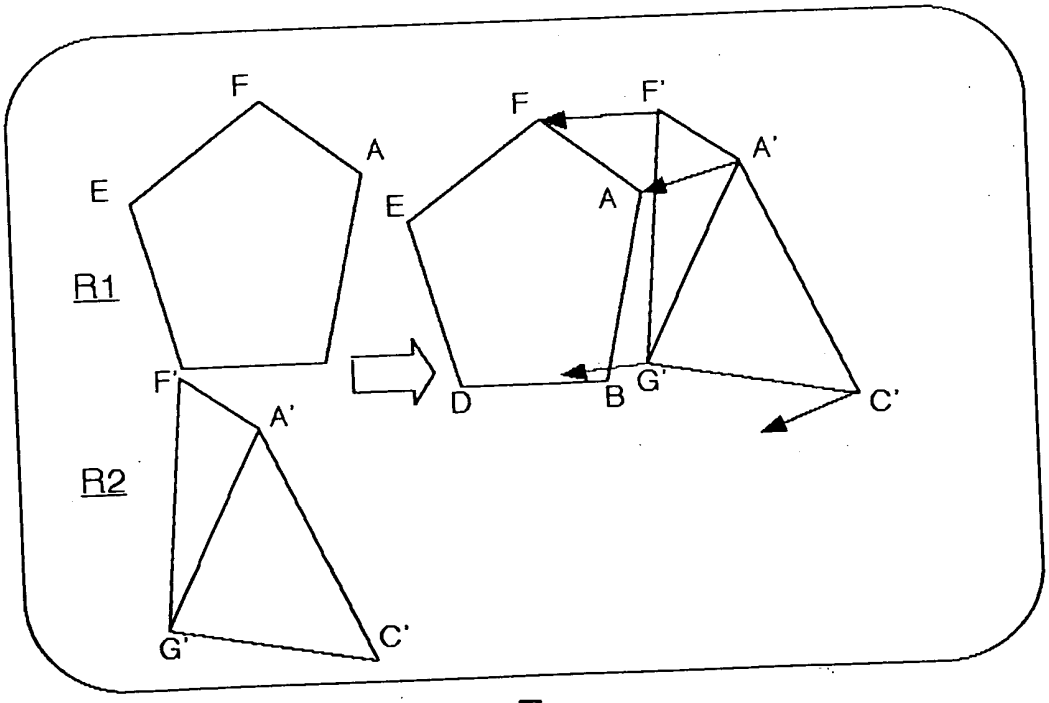

Figure 7

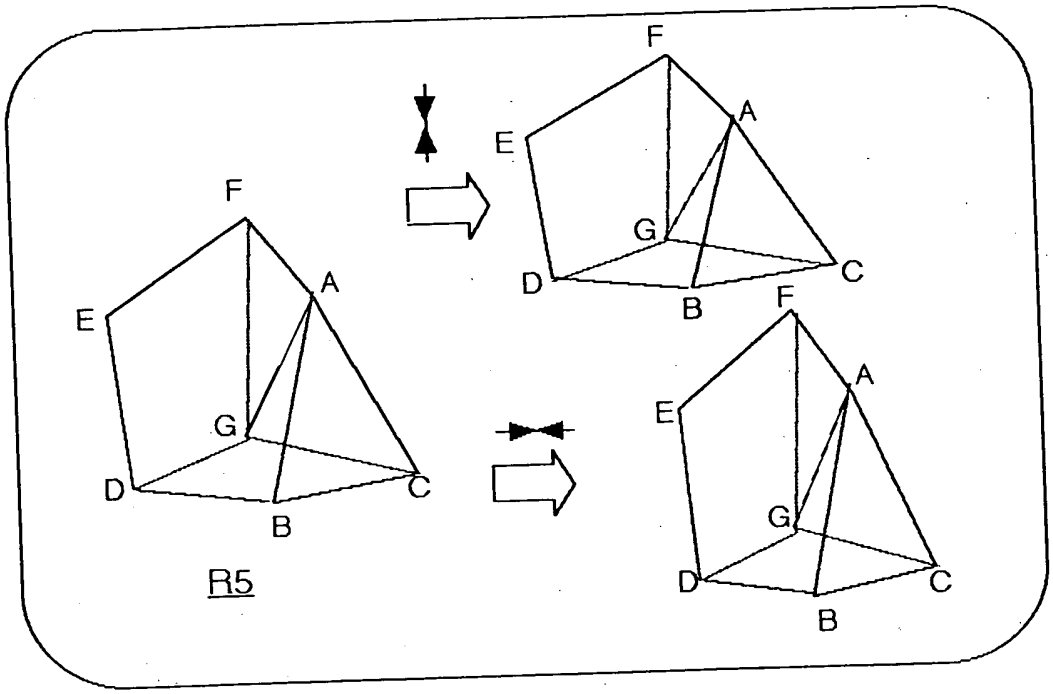

Figure 8

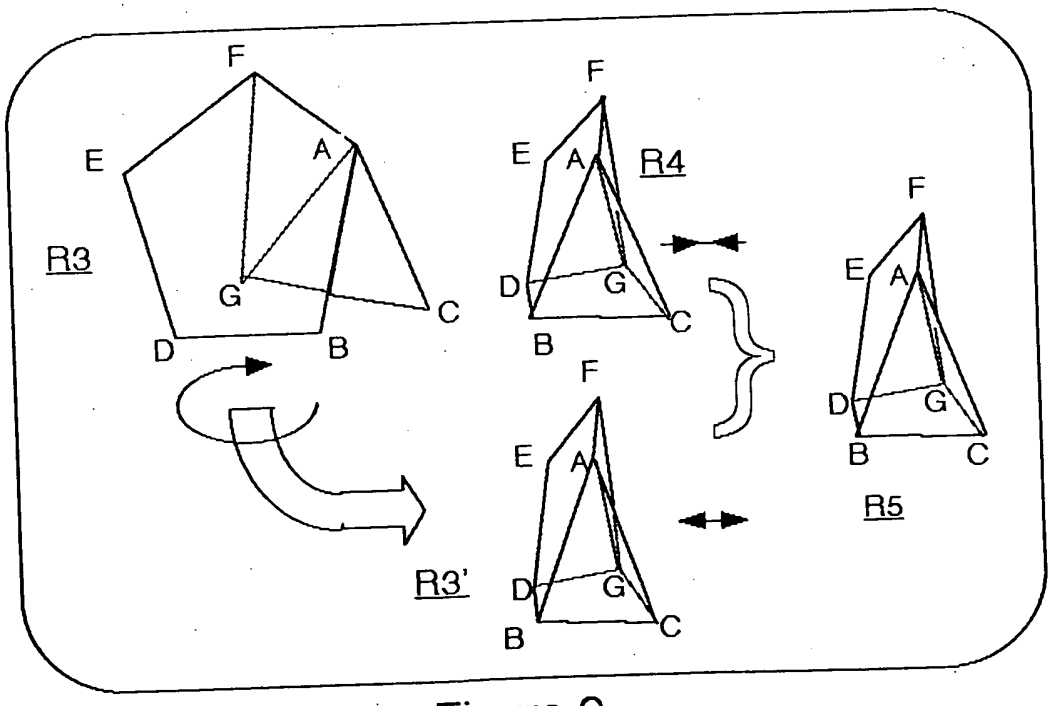

Figure 9

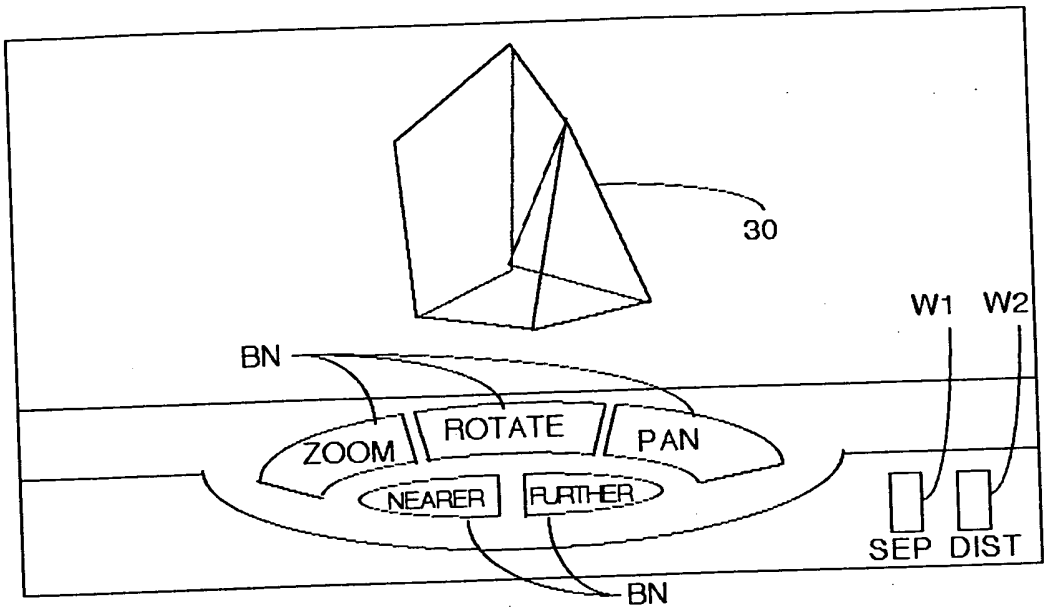

Figure 10

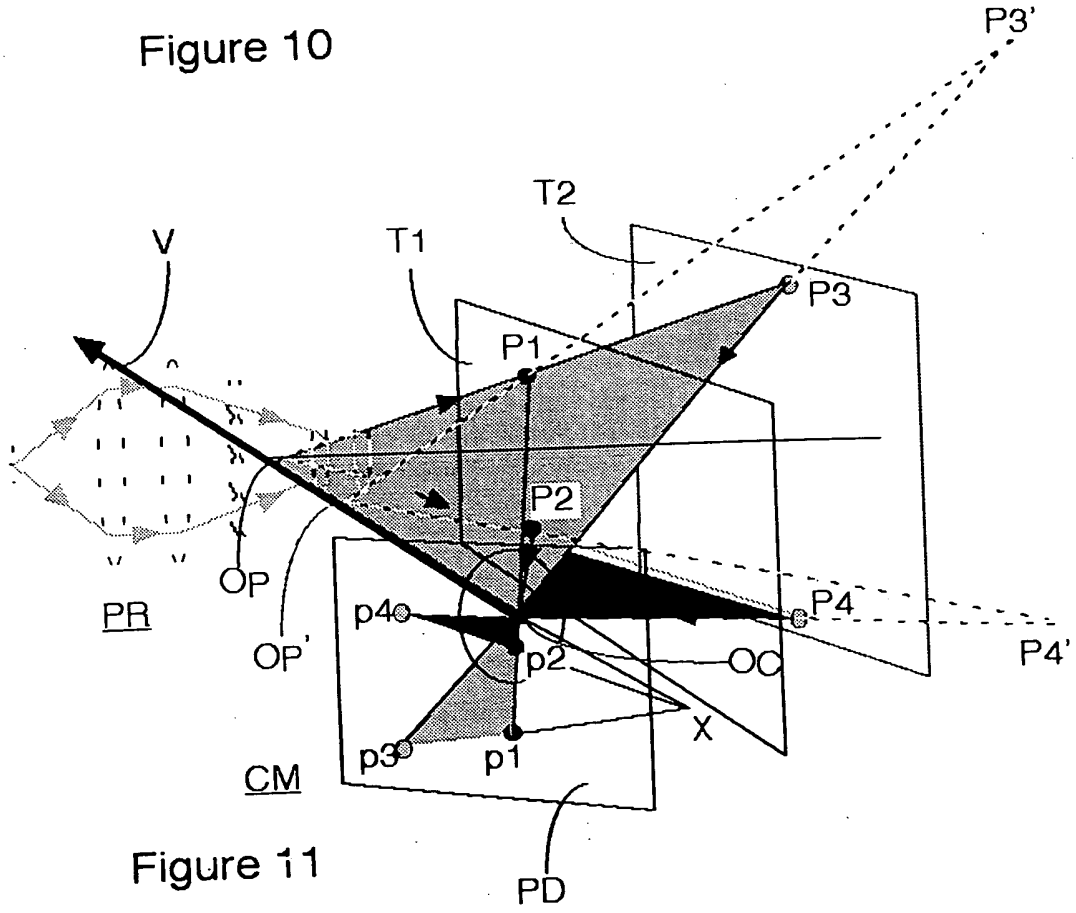

Figure 11

THIS PAGE BLANK (USPTO)